

# **Quantification of the Interacting Physical, Biological, Optical and Chemical Properties of Thin Layers in the Sea**

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## **LONG-TERM GOAL**

Our long-term goal is to develop the capability to predict thin layer formation and presence in the coastal ocean.

## **OBJECTIVES**

The central focus of our research is to investigate: the spatial and temporal scales of thin layers, the relationship between physical processes (from the microscale to the mesoscale) and thin layers, as well as the difference between layered structures in the nearshore and offshore environments. The overarching goal of our research is to ultimately determine how many physical variables are required to predict the occurrence of thin layers in the sea. In addition to this research, we also provided logistical support in the Layered Organization in the Coastal Ocean (LOCO) Program, a Departmental Research Initiative (DRI) supported by ONR.

## **APPROACH**

We undertook a several weeklong field experiments in Monterey Bay in the summers of 2005 and 2006. There were 4 major components to this work: (1) deployment of moored instruments used to measure physical processes, (2) shipboard surveys using a small vessel (33 ft) to quantify the relationship between finescale and microscale physical processes and thin layers, and to assess how local patterns of current velocity relate to thin layers, (3) AUV surveys to quantify the relationship between mesoscale physical processes, thin layers, optical properties and nutrients, and (4) acrobat tow

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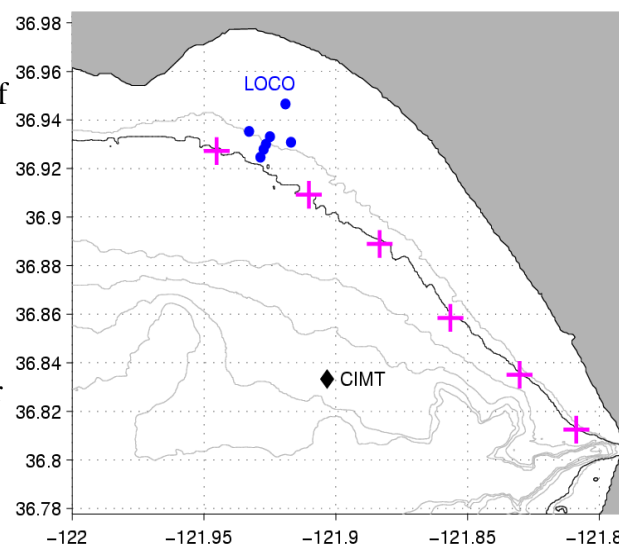
body surveys to quantify the relationship between mesoscale physical processes, thin layers and optical properties.

## WORK COMPLETED

**Instrument Deployment in the Array Site:** Instruments to measure physical processes were deployed at the array sites in 2005 and 2006. In 2006, one bottom mounted 1200 kHz ADCP was deployed at site K1 in 18.5 m of water. One bottom mounted 600 kHz ADCP, and one thermistor chain were deployed at site K2. One bottom mounted 600 kHz ADCP and one thermistor chain were deployed at site NW. Finally, one bottom mounted 300 kHz ADCP and one thermistor chain were deployed at K4 (Figure 1).

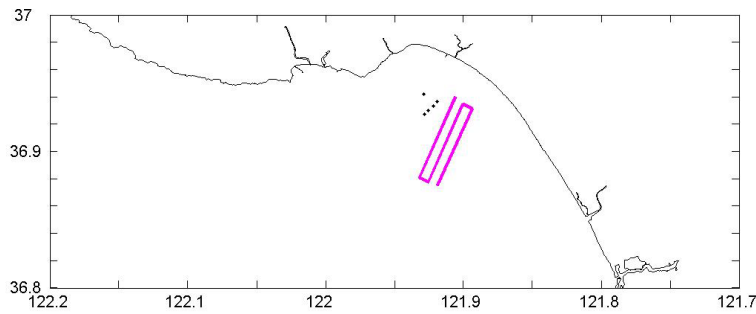
**Small Vessel Surveys:** Routine surveys were made in the array using a 33 ft vessel. Instrumentation on the small vessel included a slow-drop profiler (descent rate < 10 cm /s) equipped with a SeaBird SBE-25 CTD (T, S,  $\sigma_t$ , P), an SBE-43 ( $O_2$ ), a WET Labs WetStar fluorometer (Chlorophyll a), and a WET Labs ac-9 (absorption and attenuation at nine wavelengths). Also on the profiler was a Biospherical sensor (PAR), a Nortek ADV (finescale velocity), and a SCAMP (microstructure). In addition, a 600 kHz ADCP (current magnitude and direction) was installed on the side of the vessel. In 2006, three vessel surveys were undertaken; each encompassed a full 24-hour cycle. The 24-hr surveys were designed to span the spring-neap tidal cycle and all phases of the diurnal tidal cycle. Once on station, we profiled continuously with the high-resolution profiler every 3.5 minutes for 24 hours. There were brief breaks in our profiling cycle for downloading data from the SCAMP. The vessel mounted ADCP ran continuously during these 24-hour surveys.

**AUV Surveys:** The MBARI AUV Dorado is a 12-foot long, 21-inch diameter vehicle with a modular hardware and software design for flexible adaptation of power resources (mission duration) and sensor payload. The Dorado is equipped to measure: temperature, salinity, oxygen, optical backscattering at two wavelengths (470 and 676 nm), chlorophyll fluorescence, nitrate ( $NO_3$ ), bioluminescence, and particle size distribution in the range of 0.1 to 250  $\mu m$ . During LOCO 2006, Dorado surveys focused on variability entering the primary LOCO array. A drifter we deployed indicated mean surface flow toward the LOCO array from the south, thus the upstream survey domain extended from the array southward to Monterey Canyon. The Dorado's battery power was augmented to enable a 24-hour mission that resolved variability through a tidal cycle via 6 repeat occupations of the transect.



**Figure 1.** Location of the array sites deployed in northeastern Monterey Bay (blue circles). Sites K0 – K4 progress from onshore to offshore. Map of AUV survey waypoints (pink +) between the LOCO array and Monterey Canyon. Gray lines are isobaths.

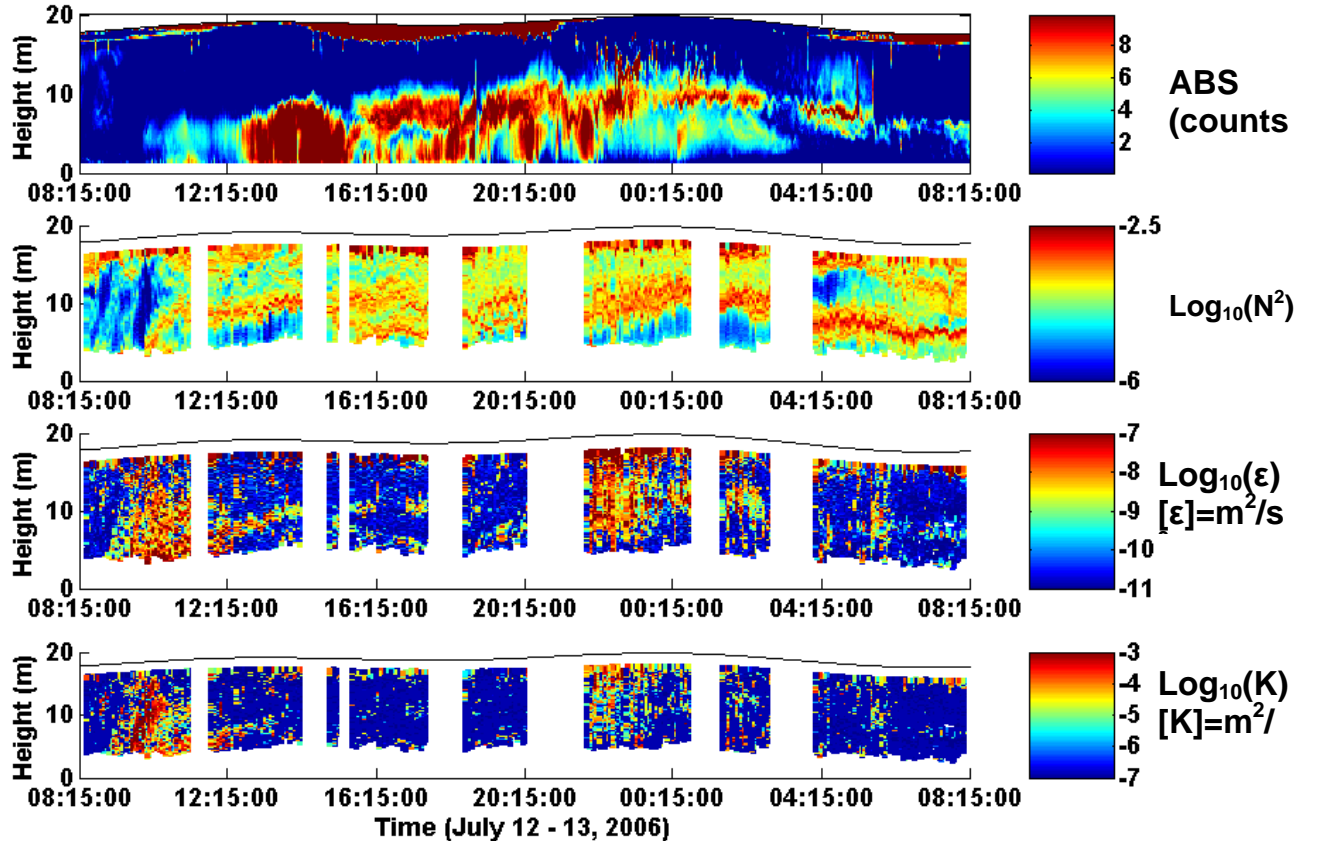
**Acrobat Surveys:** In 2006, an Acrobat tow body was equipped with a SeaBird SBE-49 FastCAT CTD (T, S,  $\sigma_t$ , P) and a WET Labs Inc. ECO-triplet sensor (chlorophyll-a, CDOM, and backscatter at 660nm). Three surveys were performed along across-isobath transects (Figure 2) southeast of the LOCO array. The first two surveys, on July 25 and 26, took place during daytime hours and were performed using the MBARI Zephyr research vessel. The third survey, on 27-28 July 2006, was an over-night expedition using a 33 ft research vessel, the Sheila-B. As the Acrobat tow body was towed along these transects, it continuously dove and ascended between the surface and within 10 m of the seafloor (down to 35 m depth).



**Figure 2.** Acrobat tow body survey tracks (pink lines) and location of the LOCO array (black dots)

## RESULTS

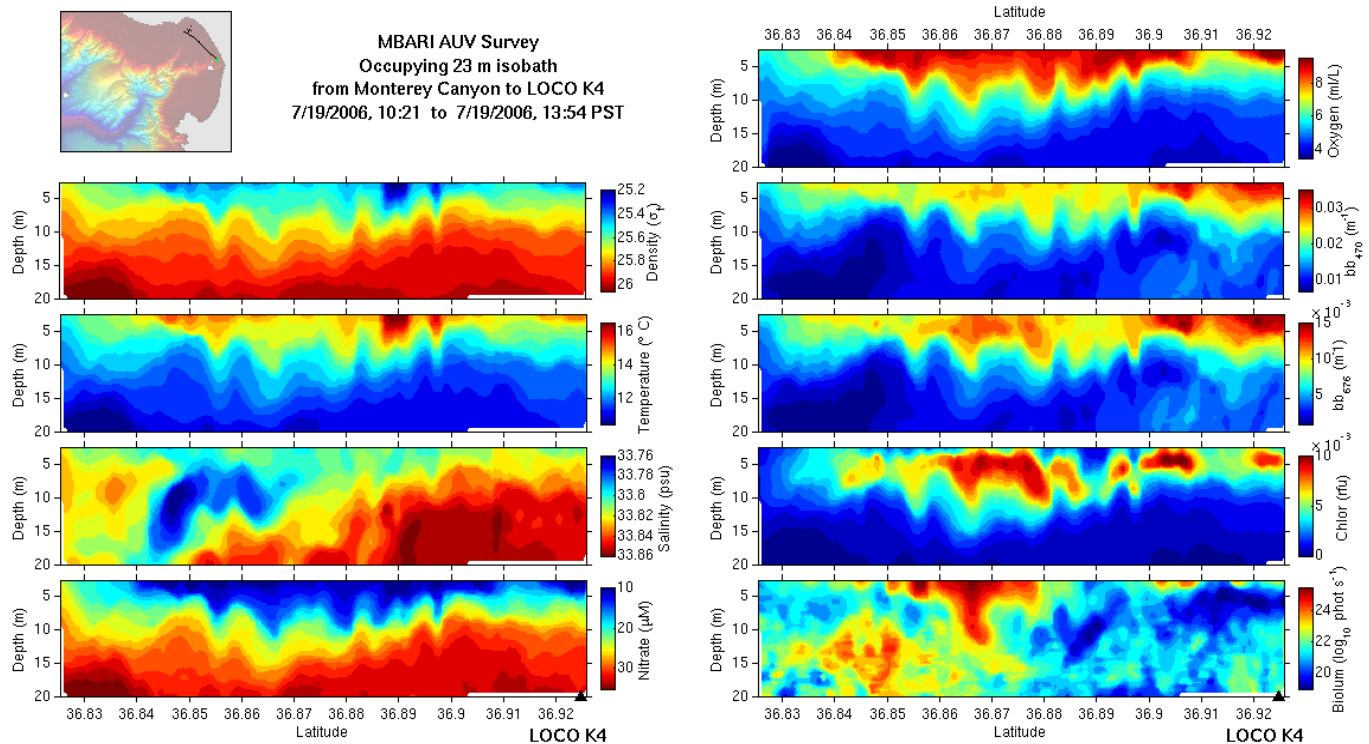
**Instrument Deployment in the Array Site:** All instruments were successfully recovered from the arrays in 2005 and 2006 with no damage to the environment. Data sets from these instruments have been downloaded, backed up in several locations, have been processed and we are now in the analysis and manuscript preparation stage.



**Figure 3: Example of overnight study results, July 12-13, 2006.** (a) Acoustic backscatter calculated from co-located ADCP; (b) buoyancy frequency squared from SCAMP measurements; (c) turbulent dissipation rate estimated from Bachelor fit to SCAMP temperature gradient spectra; (d) turbulent diffusion coefficient based on dissipation rate and buoyancy frequency using a flux Richardson number coefficient.

**Small Vessel Surveys:** The most compelling results to date arise from our three 24-h overnight surveys occurring July 12-13, July 18-19 and July 25-26, 2006. During these overnight studies we anchored in the array (near K1) and profiled continuously with our slow-drop profiler. The ADCP on board also ran continuously during these surveys. The power of these studies lies in the capability of the slow-drop profiler to collect continuous, high-resolution profiles of chlorophyll-a fluorescence and the vertical structure of the water column during periods of layer formation, maintenance and dissipation. The entire overnight period for July 12-13 is presented in Figure 3. In the top panel, a distinct layer in the acoustic backscatter is evident from about 2300 hours onwards, and is co-located with a strongly stratified layer (2<sup>nd</sup> panel Figure 3), particularly in the early morning hours. Interestingly, the dissipation of the layer at around 0600 hours is not associated with either a distinct change in the stratification (2<sup>nd</sup> panel Figure 3) or a pronounced mixing event (3<sup>rd</sup> and 4<sup>th</sup> panels Figure 3). As such, it appears that this layer dissipated through a biological process, mostly like migration in response to sunrise.

**AUV Surveys:** The monitoring of physical, nutrient, and optical conditions between Monterey Canyon and the LOCO array for a full tidal cycle revealed important processes influencing conditions and layer structures in the LOCO study region. These processes are clearly evident in an animation of the data from 6 repeat sections ([http://www.mbari.org/staff/ryjo/loco2006/LOCO\\_Dorado\\_anim.html](http://www.mbari.org/staff/ryjo/loco2006/LOCO_Dorado_anim.html)). One frame from this animation is shown in Figure 4.

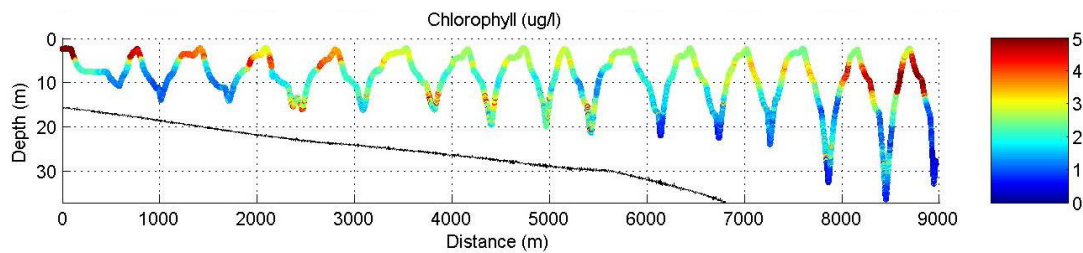


**Figure 4.** One of the Dorado AUV's repeat vertical sections of physical, nutrient, and optical conditions between Monterey Canyon and the LOCO array (K4).

These observations showed flow of relatively cold, low oxygen, high density, high-nutrient waters into the LOCO array below the thermocline. This process is likely due to the amplified internal tide over the canyon, which pumps waters from the canyon onto the shelf. This process likely influenced nutrient availability and stratification in the LOCO array. The AUV data also reveal propagation of internal waves into the array region. Internal waves were evident in many LOCO data sets, and the rapid repeat sections from the AUV defined at least one of the ray paths for these internal waves. Hydrographic measurements revealed interleaving of water masses. Bio-optical measurements revealed both subsurface and surface patchiness in chlorophyll fluorescence on the scale of internal waves, as well as complex relationships between the patchiness of chlorophyll fluorescence, optical backscatter, and bioluminescence, and intense stimutable bioluminescence - even during the day.

**Acrobat Surveys:** The data from all 3 Acrobat surveys show similar across-isobath biological and physical structure. At the inshore (15-20 m depth) end of each transect, a moderately thin (4-6 m thick) patch of chlorophyll was present at the surface, and a broad subsurface patch of chlorophyll was found further offshore (40-60 m depth; Figure 5). Between these 2 features, small concentrations of chlorophyll were present at the surface, while a moderately strong thin layer of chlorophyll was present at depth (~ 10 m below surface). Preliminary results indicate that the thin phytoplankton layers observed in these transects were associated with a salinity minimum intrusion.





**Figure 5. Acrobat profiles along transect 1 on July 27 2006.**

**Remote Sensing:** Remote sensing is critical to understanding the oceanographic variability that influenced the bay environment during the LOCO field programs. Our group has processed MODIS satellite imagery from both LOCO field programs with custom atmospheric correction using the high-resolution bands of MODIS. This processing produced much higher quality imagery than the standard MODIS processing and revealed major influences of offshore and recently upwelled waters on the bay during the LOCO field programs. Additionally airborne remote sensing during LOCO 2006 provided a highly detailed view of conditions during the middle of the experiment (Figure 6), when we were conducting high-resolution overnight sampling in situ. This remote sensing data clearly showed that the LOCO site was in the warmest waters of the bay, and that extreme patchiness in the phytoplankton was being caused by stirring of the bay by a cyclonic eddy. This stirring created colored surface streaks throughout the northern bay.

**Publications:** At this early date, this grant has directly contributed to five publications in peer-reviewed journals (2 in revision; 2 published in 2008; 1 published in 2007). In the list provided below, the names of graduate students supported by this grant are underlined.

Cheriton OM, MA McManus, MT Stacey, JV Steinbuck, and JP Ryan. In revision. Physical and biological controls on the maintenance and dissipation of a thin phytoplankton layer. *Marine Ecology Progress Series*.

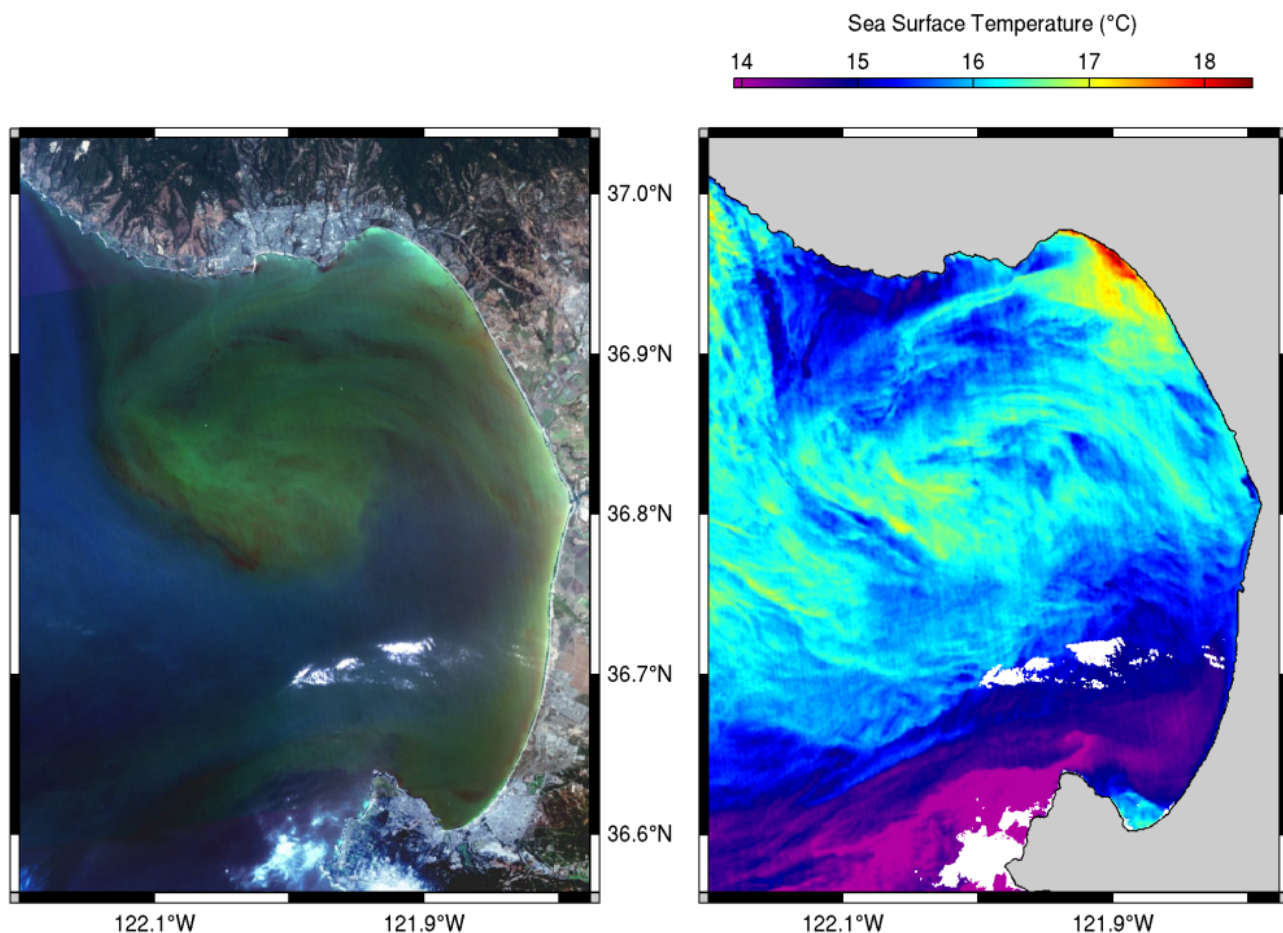
Steinbuck JV, MT Stacey, MA McManus and OM Cheriton. In revision. Turbulence and swimming dynamics in a phytoplankton thin layer. *Limnology and Oceanography*.

McManus MA, RM Kudela, MV Silver, GF Steward, JM Sullivan and PL Donaghay. 2008. Cryptic blooms: Are thin layers the missing connection? *Estuaries and Coasts*. 31: 396-401.

Ryan JP, MA McManus, JD Paduan and FP Chavez. 2008. Phytoplankton thin layers caused by shear in frontal zones of a coastal upwelling system. *Marine Ecology Progress Series*. 354:21-34.

Stacey MT, MA McManus and J Steinbuck. 2007. Convergences and divergences and thin layer formation and maintenance. *Limnology and Oceanography*. 52(4): 1523-1532.

In addition, four additional manuscripts are being written for the **Continental Shelf Research** special issue: “*The Structure and Dynamics of Thin Layers: The Layered Organization in the Coastal Ocean Experiment*”.



**Figure 6:** Color and SST imagery for July 19, 2006 from the MODIS Airborne Simulator.

## IMPACT/APPLICATIONS

Patterns in biological distribution cannot be interpreted without an understanding of physical oceanographic processes. Through our analysis of simultaneous measurements of physical processes and thin layers, we have found that physical processes from the microscale to the mesoscale each have critical impacts on thin layer dynamics (Dekshenieks et al. 2001, McManus et al. 2003, McManus et al. 2005, Stacey et al. 2007, Cheriton et al. 2007, Ryan et al. 2008). For this reason, our work provides a critical framework for other ONR LOCO Projects. The ability to make the translation between physical processes over a range of scales, and the mechanisms contributing to thin layer dynamics will ultimately allow us to predict the presence of thin layers in the sea.

## RELATED PROJECTS

Related projects: (1) D. Van Holliday & Charles F. Greenlaw (BAE Systems): “Layered Organization in the Coastal Ocean: Acoustical Data, Acquisition, Analyses and Synthesis”, (2) Percy L. Donaghay & James M. Sullivan (URI): “Layered Organization in the Coastal Ocean: 4-D Assessment of Thin Layer Structure, Dynamics and Impacts”, (3) Timothy J. Cowles (OSU): “Finescale Planktonic Vertical Structure: Horizontal Extent and the Controlling Physical Processes”, (4) Jan E.B. Rines (URI): “LOCO: Characterization of Phytoplankton in Thin Optical Layers”, (5) David M. Fratantoni & Nelson G. Hogg (WHOI): “The Physical Context for Thin Layers in the Coastal Ocean”, (6) Louis



Goodman (U Mass Dartmouth): “AUV Turbulence Measurements in the LOCO Field Experiments”, and (7) Alfred K. Hanson (URI): “An Investigation of the Role of Nutrient Gradients in the Episodic Formation, Maintenance and Decay of Thin Plankton Layers in Coastal Waters”. Additional related projects include (8) Kelly Benoit-Bird (OSU) “Predator effects on dense zooplankton aggregations in the coastal ocean”, funded by the ONR Young Investigators Program.

## **PUBLICATIONS**

Allredge AL, TJ Cowles, S MacIntyre, JEB Rines, PL Donaghay, CF Greenlaw, DV Holliday, MM **Deksheniaks**, JM Sullivan and JRV Zaneveld. 2002. Occurrence and mechanism of formation of a dramatic thin layer of marine snow in a shallow Pacific fjord. *Marine Ecology Progress Series*. 233: 1-12.

Cheriton OM, MA **McManus**, MT **Stacey**, JV Steinbuck, and JP **Ryan**. In revision. Physical and biological controls on the maintenance and dissipation of a thin phytoplankton layer. *Marine Ecology Progress Series*.

Cheriton OM, MA **McManus**, DV Holliday, CF Greenlaw, PL Donaghay and T Cowles. 2007. Effects of mesoscale physical processes on thin zooplankton layers at four sites along the West Coast of the U.S. *Estuaries and Coasts*. 30(4): 1-16.

**Deksheniaks** MM, PL Donaghay, JM Sullivan, JEB Rines, TR Osborn and MS Twardowski. 2001. Temporal and Spatial Occurrence of Thin Phytoplankton Layers in Relation to Physical Processes. *Marine Ecology Progress Series*. 223: 61-71.

Fong DA and MT **Stacey**. 2003. Horizontal Dispersion of a Near Bed Coastal Plume. *Journal of Fluid Mechanics*. 489: 239-267.

Holliday DV, PL Donaghay, CF Greenlaw, DE McGehee, MA **McManus**, JM Sullivan and JL Miksis. Advances in Defining Fine- and Micro-scale Pattern in Marine Plankton. 2003. *Aquatic Living Resources*. 16(3): 131-136.

Lacy JR, **Stacey** MT, Bureau JR, and SG Monismith. 2003. The Interaction of Lateral Baroclinic Forcing and Turbulence in an Estuary. *J. Geophys. Res.* 108(C3): 3089.

**McManus** MA, RM Kudela, MV Silver, GF Steward, JM Sullivan and PL Donaghay. 2008. Cryptic blooms: Are thin layers the missing connection? *Estuaries and Coasts*. 31: 396-401.

**McManus**, MA, OM Cheriton, PJ Drake, DV Holliday, CD Storlazzi, CF Greenlaw, PL Donaghay. 2005. Thin Layers and the Transport and Retention of Marine Plankton. *Mar. Ecol. Prog. Ser.* 301: 199-215.

**McManus** MA, AL Allredge, A Barnard, E Boss, J Case, TJ Cowles, PL Donaghay, L Eisner, DJ Gifford, CF Greenlaw, C Herren, DV Holliday, D Johnson, S MacIntyre, D McGehee, TR Osborn, MJ Perry, R Pieper, JEB Rines, DC Smith, JM Sullivan, MK Talbot, MS Twardowski, A Weidemann and JRV Zaneveld. 2003. Changes in Characteristics, Distribution and Persistence of Thin Layers Over a 48-Hour Period. *Marine Ecology Progress Series*. 261: 1-19.

Rines JEB, PL Donaghay, MM **Dekshenieks**, JM Sullivan and MS Twardowski. 2002. Thin Layers and Camouflage: Hidden Pseudo-nitzschia populations in a fjord in the San Juan Islands, Washington, USA. Marine Ecology Progress Series. 225: 123-137.

**Ryan** JP, MA **McManus**, JD Paduan and FP Chavez. 2008. Phytoplankton thin layers caused by shear in frontal zones of a coastal upwelling system. Marine Ecology Progress Series. 354:21-34.

**Stacey** MT and DA Ralston. Submitted. The Scaling and Structure of the Estuarine Bottom Boundary Layer. Journal of Physical Oceanography.

**Stacey** MT, MA **McManus** and J Steinbuck. 2007. Convergences and divergences and thin layer formation and maintenance. Limnology and Oceanography. 52: 1523-1532.

**Stacey** MT. 2003. Estimation of Dispersive Transport of Turbulent Kinetic Energy from Acoustic Doppler Current Profiler Data. J. Atmos. Ocean. Tech., 20(6): 927-935.

Steinbuck JV, MT **Stacey**, MA **McManus** and OM Cheriton. In revision. Turbulence and swimming dynamics in a phytoplankton thin layer. Limnology and Oceanography.

*(\*Please note McManus formerly Dekshenieks. Names of PIs are in bold. Names of students supported on this work are underlined.)*